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MAGNETIZATION PROCESS AND TORQUE CURVES IN HCP COBALT

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Abstract-Magnetization measurements were made in hcp cobalt by using a very low frequency vibrating sample magnetometer in the same external field range where the torque curve analyses were performed. The anomalously small value of K_{u1} analyzed from the torque curves in the very low field region below 0.3T were found to be attributable to the appearance of a multiple domain configuration. The applicability of the least mean square analysis, developed by one of the present authors, for unsaturated torque curves, was confirmed within the range where the single domain configuration takes place.

INTRODUCTION

In developing new permanent magnet materials or in improving soft magnetic materials, it is necessary to know the complicated magnetization process. A large number of experimental and theoretical studies for this process have been accumulated in various kinds of magnetic materials. However, even in a simplest case of a uniaxial ferromagnet such as pure cobalt, there still remain some important phenomena to be investigated more precisely.

Magnetization curves in single crystal hcp cobalt were studied by Pauthenet et al.[1] along the directions paralell and perpendicular to the external magnetic field. According to their results, the magnetization curves could be explained by considering a simplified domain configuration and the rotation of the magnetization vector in each domain at the expense of the uniaxial magnetocrystalline anisotropy energy.

On the contrary, a problem had long been left unsolved in analysing torque curves in hcp cobalt [2], where the determined uniaxial magnetocrystalline anisotropy constants were largely dependent on the intensity of the external field. The inadequacy of the usual Fourier analysis was pointed out by the present author [3], and an alternative method was proposed using the least mean square routine. The values of the first and the second uniaxial magnetocrystalline anisotropy constants, K_{u1} and K_{u2}, thus determined, were confirmed by Paige et al.[4]. It was shown [5] that this method was not only effective in high field region, but also in a weak field region as low as 0.3T, where the maximum torque intensity was only a half of the saturated value. Below this field limit, the determined value of K_{u1} decreased with further decreasing of the external field.

The method of determining the anisotropy constants proposed by the present authors is especially effective for such materials as recently developed very high energy permanent magnets, in which saturated torque curve observations are almost impossible in the avairable external field range [6]. To apply this method to the case of $Ho_2 Fe_{14} B$, for which the anisotropy energy is higher than in $Nd_2Fe_{14}B$, it is necessary to clarify the magnetization process below the critical field.

In the present paper, the magnetization process in pure hcp cobalt below the critical field is compared with observed torque curves.

MAGNETIZATION MEASUREMENTS

By using a very low frequency vibrating sample magnetometer, measurements of magnetization curves were made. The frequency of the magnetometer was 1 second. The specimen was a thin circular disc of single crystal cobalt, which was the same that used in the torque curve measurements [5]. The surface of the sample was parallel to a $(10\bar{1}0)$ plane.

Observed magnetization curves with the external field along c-axis and perpendicular to c-axis are shown in Fig.1. As seen in this figure the magnetization along c-axis becomes technically saturated at a very low field of 0.04T. From this fact the actual demagnetization factor is estimated to be 0.28. This value is smaller than 0.48, which was estimated, previously [5] by considering an approximate ellipsoidal shape. The magnetization perpendicular to the c-axis became saturated above 1T.

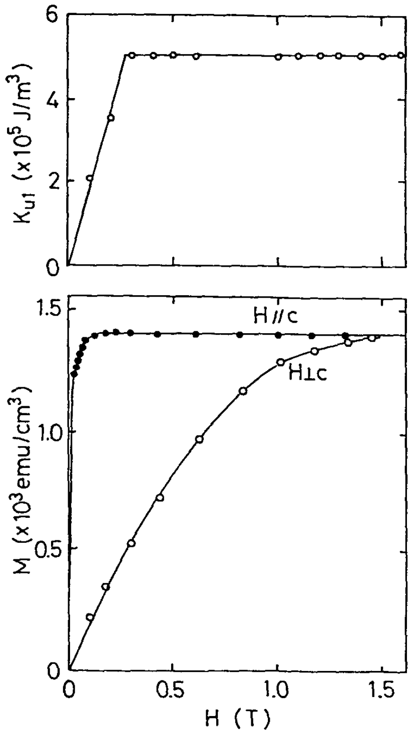

Fig.1 A comparison of the magnetic field dependences of the magnetocrystalline anisotropy constant K_{u1} and the magnetization curves along and perpendicular to the c-axis in pure hcp cobalt at room temperature.

To compare to the torque curves the magnetization at a constant external field was measured as a function of the angle of the external field with respect to the easy direction. The angle dependence of the magnetization at the external field of 0.1T is plotted in Fig.2. The intensity of this external field is lower than the critical field above which the magneto-

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crystalline anisotropy constant can be uniquely determined.

The magnetization at the constant field of 0.3T, which is just above the critical value, was plotted in Fig.3 as a function of the angle. From this figure it is seen that the magnetization is still strongly dependent of the angle.

COMPARISON WITH TORQUE CURVE MEASUREMENTS

It was pointed out by the present author [5] that the unusual decrease of the analyzed magnetocrystalline anisotropy constant below 0.3T is due to an appearance of a multiple domain configuration. How-

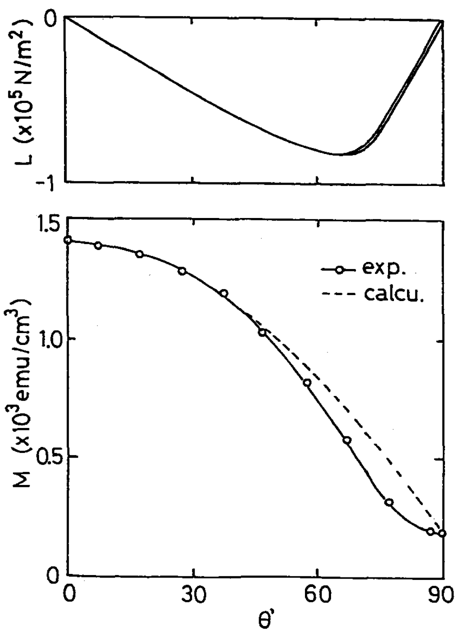

Fig.2 Angle dependences of the magnetization and the torque intensity at H=0.1T.

ever, this value of 0.3T is much higher than the technical saturation field of the magnetization curve along the easy axis shown in Fig.1.

To find out in which angle range the multiple domain configuration takes place, observed torque curve at the external field of 0.1T is compared in Fig.2 with the magnetization data. However, it is not easy to point out the angle range by comparing the magnetization data directly with the observed torque curve.

The observed angle dependence of the magnetization at the constant field of 0.3T is compared in Fig.3 with the torque curve observed at the same external field. It is not clear to find whether or not the multiple domain configuration takes place by only comparing these two curves in Fig.3. One thing clear is that the angle dependence of the magnetization at 0.1T has concavity in the highest angle region, while it is not seen in the curve at 0.3T.

DISCUSSION

To find out which of the two possible domain configurations is more stable, the corresponding free energies must be compared. In the case of single

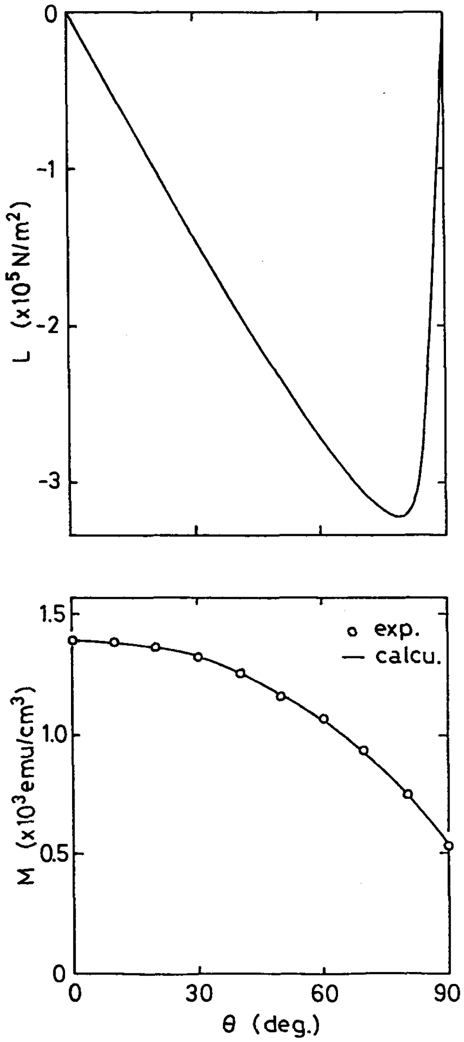

Fig.3 Angle dependences of the magnetization and the torque intensity at H=0.3T, where the maximum torque intensity is yet much smaller than the saturated value.

domain structure, the free energy is expressed as,

$$F_{sd} = K_{u1}\sin^2\theta + K_{u2}\sin^4\theta - M_sH\cos(\theta'-\theta) + \frac{1}{2}NM_s^2, \quad (1)$$

where M_s is the saturation magnetization, H is the external field, N is the demagnetization factor, θ is the angle between the easy axis and the direction of the magnetization and θ' is the angle between the easy axis and the direction of the external field. For a multiple domain configuration the free energy is written as,

$$F_{md} = a[K_{u1}\sin^2\theta + K_{u2}\sin^4\theta - M_sH\cos(\theta'-\theta)]$$
$$+b[K_{u1}\sin^2\phi + K_{u2}\sin^4\phi - M_sH\cos(\theta'-\phi)] + \frac{1}{2}NM^2 \quad (2)$$

where a and b are the volume ratio of the majority and the minority domains, θ and ϕ are the angles between the easy axis and the directions of the magnetization of the majority and minority domains, respectively.

In the case of single domain configuration, the equilibrium condition for the magnetization vector is derived from eq.(1) by differentiating with θ, as

$$2K_{u1}\sin\theta\cos\theta + 4K_{u2}\sin^3\theta\cos\theta - M_sH\sin(\theta'-\theta) = 0. \quad (3)$$

The intensity of the magnetization along the direction of the external field can be calculated from this equation by substituting the anisotropy constants determined from the torque analysis at sufficiently high field range and the M_s value determined from the present magnetization measurement along the easy direction. Thus calculated values at the external field of 0.1T are compared in Fig.2 with the experimental values. From this figure it is seen that the experimental points start to deviate around 45°, and coincide again with the calculated curve at 90°.

A possible way to estimate the critical angle from which the multiple domain structure takes place is to use the instability condition for the single domain configuration,

$$N M_s > H\cos(\theta' - \theta). \quad (4)$$

In the case of H=0.1T, this condition reduces to

$$\theta' > 70°. \quad (5)$$

Evidence for the appearance of the multiple domain configuration can also be seen as a small hysteresis around the hard axis of the torque curve at H=0.1T shown in an expanded scale in Fig.4. The hysteresis appears in the highest angle region above 65°. This critical angle coincide well with the theoretical value mentioned above. On the contrary, This angle is apparently higher than the value of 45°, from which the calculated value of the magnetization starts to deviate from the experimental points.

On the other hand, in the case H=0.3T, the condition (4) is not satisfied even at θ'=90°, and no multiple domain configuration would be expected. Thus, the possible domain configuration can be explained from the simple free energy expression.

The analyzed value of K_{u1} from an unsaturated torque curve in a low field region by using the least mean square routine reflects the above mentioned situation. A saturated value of K_{u1} can be obtained in the case of single domain configuration.

The present investigation seems to be effective to estimate the lower limit, H_k of the field necessary to determine the magnetocrystalline anisotropy constants in recently developed high energy permanent magnet materials of $R_2Fe_{14}B$. This field is

$$H_k \fallingdotseq 0.25\ H_a\ , \quad (6)$$

where H_a is the anisotropy field. In the case of $Nd_2Fe_{14}B$, the maximum field of an electro-magnet is just above the critical field [6].

CONCLUSIONS

By comparing the observed magnetization data with torque curves, it became possible to point out the angle range where the multiple domain configuration takes place. The instability of the single domain structure is explained theoretically from a simple energetic consideration. If we exclude the multiple domain configuration range in analysing observed torque curves, it becomes possible to determine precisely the magnetocrystalline anisotropy constants.

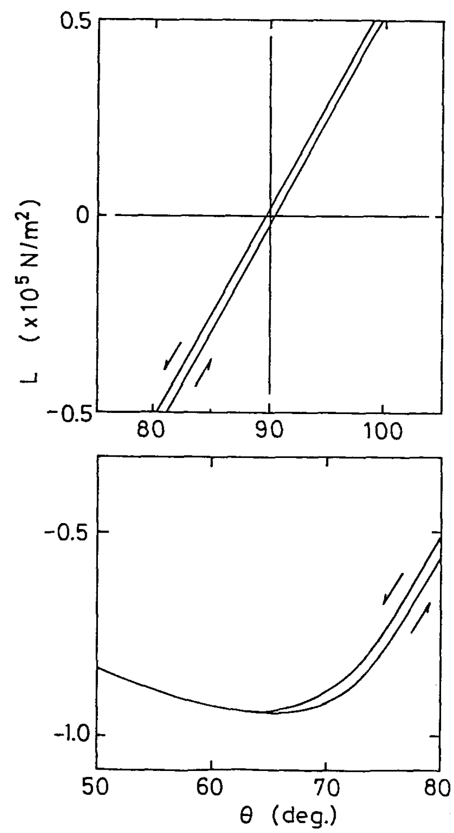

Fig.4 Observed hysteresis in the torque curve at H=0.1T shown in an expanded scale.

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